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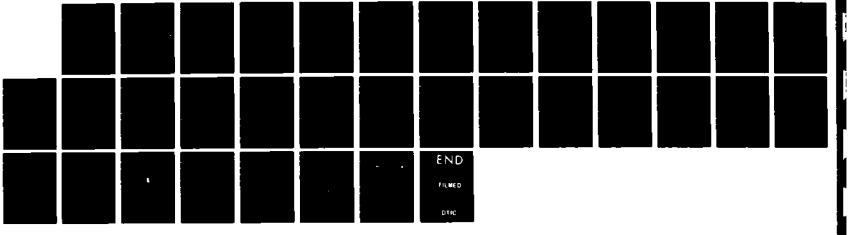

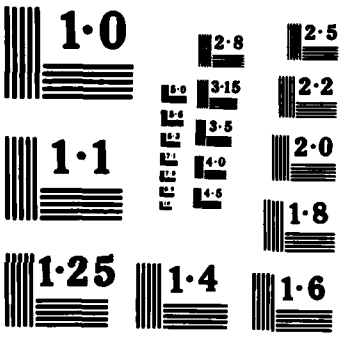

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SPECKLE IMAGE RECONSTRUCTION

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STEWARD OBSERVATORY

UNIVERSITY OF ARIZONA

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STEWARD OBSERVATORY PROGRESS REPORT

This report contains results obtained from observations using the University of Arizona 2.3 meter telescope, the Kitt Peak National Observatory 4 meter telescope and the Multiple Mirror Telescope.

Kitt Peak Natioinal Observatory, a division of the National Optical Astronomy Observatories, is operated by the Association of Universities for Research in Astronomy, Inc., under contract to the National Science Foundation.

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TABLE OF CONTENTS

1. SUMMARY OF WORK DONE

This is a summary review of work completed, work in preparation for publication and work currently in progress. The format of this report consists of a set of abstracts summarizing each accomplishment or objective. Two appendices contain supporting exhibits.

1.1 High Resolution Imaging Potential of MMT

Our showpiece accomplishment during this grant interval is the implementation and validation of the world's largest, full (u,v)-plane coverage optical imaging array — the 6.9m Multiple Mirror Telescope (MMT). Also contained in this work is our second showpiece accomplishment, the demonstration of a newly developed image reconstruction technique which is self-calibrating for seeing. This algorithm was used to display the coherent, phased PSF for the MMT (Figure 1) obtained through the atmosphere using an unresolvable star. This work has been submitted for publication in Applied Optics. The implementation and validation of this cophasing system for the MMT, and commensurate image reconstruction techniques, are crucial to the further development and any significant implementation of diffraction limited imaging processes and systems.

THE MULTIPLE MIRROR TELESCOPE* AS A PHASED ARRAY TELESCOPE
E. K. Hege, J. M. Beckers+ P. A. Strittmatter and D. W. McCarthy

> By adjusting the optical pathlengths of the MMT telescopes, it is possible to make the MMT into a phased array with a 6.86 m baseline. A coherent, phased focus can be achieved with tilted focal planes if the tilt angle is chosen so that the internal phase differences exactly compensate the external phase differences. This amounts to a slight change in configuration such that the beams are brought together at f/8.39 rather than the originally designed f/9. We summarize experiments which have used the MMT subapertures as a phased array and as a coherent, phased telescope,and present a simple analysis of the tilted focal plane geometry for coherent observation. The phased operation of the MMT is important not only for obtaining high angular resolution, but also for obtaining the higher detection sensitivity which results from the better discrimination against the sky emission

background for infrared diffraction limited images. Full-aperture (six-beams), diffraction-limited results for the unresolved source Gamma Orionis, the well-known close binary Capella and the resolved red supergiant Betelgeuse, (including a diffraction limited differential speckle image of the latter) are presented as preliminary demonstration of the potential capabilities of this configuration.

Applied Optics, 24 (1985)

1.2 Earth Satellite Observations

Our third showcase accomplishment, the first measurement from a ground based site of a geosynchronous near Earth satellite, albeit only in one (vertical) dimension, relates to the current Air Force objective of space object identification. In the earlier stages of the development of the fully-phased, coherent imaging MMT, several two beam speckle autocorrelation function measurements were made. From these we infer a diameter of 4.9m (±2.0m) for the geostationary communications satellite FLTSATCOM1.

SIZE MEASUREMENT OF A GEOSYNCHRONOUS SATELLITE USING THE MMT
K. Hege and E. Jensen

We have used the Multiple Mirror Telescope as a two-beam interferometer to produce a one-dimensional size estimate for a geosynchronous Earth satellite using speckle autocorrelation techniques. We find the vertical diameter of FLTSATCOM1 to be 4.9±2.0m.

(Preprint)

1.3 Asteroid/Planetary Satellite Measurements

One of the principle requirements for ground based space object identification is the validation of the techniques employed, for example, statistical precision attainable as a function of signal intensity and integration time, and image fidelity vis a vis object ground truth. The Steward Observatory asteroid/planetary satellite imaging project is a fertile experimental environment for such tests. Especially germain is our newly developed technique for asteroid image modeling constrained by

speckle autocorrelation function data, and several new image reconstruction techniques which have either proven to be, or appear to have the potential of being, robust to the application to specklegrams dominated by Poisson noise uncertainties.

Extensions of this work, especially to Saturnian satellites and geosynchronous Earth satellites, both classes of objects being of similar angular extent and having known ground truth, will be crucial in achieving the required calibrations and validations.

PLUTO
Central Bureau for Astronomical Telegrams
International Astronomical Union

E. K. Hege and J. Drummond, Steward Observatory, write that a well-calibrated speckle interferometric observation made on Feb.16.44 UT with the Harvard speckle camera at a single 1.8-m mirror of Multiple Mirror telescope showed the satellite 1978 PI to be separated the primary by 0.168 $^{\circ}$ 0.01 in p.a. 7.3. The discordance in position angle confirms that found earlier (Hege et al. 1982, Icarus 50, 72) and shows the satellite's orbital inclination (with respect to the plane of the sky) to be $94^{\circ} \pm 1^{\circ}$, a decrease of $1^{\circ} \pm 1^{\circ}$ over the prediction (and in contrast to a $3^{\circ} \pm 4^{\circ}$ increase over prediction observed in 1980 June). This suggests that the expected eclipses of the system should be occurring when Pluto next becomes favorably placed, although events may be delayed.

IAU Circular #3986 (1984)

SPECKLE INTERFEROMETRY OF ASTEROIDS I. 433 EROS
J. D. Drummond, W. J. Cocke, E. K. Hege, and P. A. Strittmatter and J. V. Lambert

Analytic expressions for the semimajor and semiminor axes and an orientation angle of the ellipse projected by a triaxial ellipsoid (an asteroid) and of the ellipse segment cast by a terminator across the ellipsoid as functions of the dimensions and pole of the body and the asterocenteric position of the Earth and Sun are derived. Applying these formulae to observations of the Earth-approaching asteroid 433 Eros obtained with the speckle interferometry system of Steward Observatory on December 17-18, 1981, and January 17-18, 1982, the following dimensions are derived: (40.5 $\pm$ 3.1 km) x (14.5 $\pm$ 2.3 km) x (14.1 $\pm$ 2.4 km). Eros' north pole is found to lie within 14° of RA = $0^{h}16^{m}$ Dec. = $+43^{\circ}$ (ecliptic longitude 23°, latitude $+37^{\circ}$). Other than knowing the rotation period of Eros, these results are completely independent of any other data, and in the main confirm the results

obtained in the 1974-75 apparition by other methods. These dimensions, together with a lightcurve from December 18,1981, lead to geometric albedo of 0.156 ± 0.010. A series of two-dimensional power spectra and autocorrelation functions of the resolved asteroid clearly show it spinning in space.

Icarus 61, 132 (1985)

FIENUP IMAGE RECONSTRUCTION OF EROS
K. Hege and J. Cocke

We have applied the Fienup iterative process to the reconstruction from a seeing calibrated speckle autocorrelation function accumulated from specklegrams of Eros observed with the Steward Observatory 2.3m telescope. The resultant concave (sky projected) image intensity contour is inconsistent with the simple triaxial model interpretation of Drummond et al.and may explain some of the large residuals in that simple analysis. A second analysis by Bates yields a similar concave image profile.

(Unpublished)

SPECKLE INTERFEROMETRY OF ASTEROIDS II. 532 HERCULINA
J. D. Drummond, E. K. Hege, W. J. Cocke, J. D. Freeman, J. C. Christou and R. P. Binzel

Speckle interferometry of 532 Herculina performed on January 17, 18, 1982, yields triaxial ellipsoid dimensions of (263± 14) x (218 ± 12) x (215 ± 12) km, and a north pole for the asteroid within 7° of RA = 7^h47^m and Dec = -39° (ecliptic coordinates = 132° = -59°). In addition, a "spot" some 75% brighter than the rest of the asteroid is inferred from both speckle observations and Herculina's lightcurve history. This bright complex, centered at asterocentric latitude -35°, longitude 145° - 165°, extends over a diameter of 55° (115 km) of the asteroid's surface. No evidence for a satellite is found from the speckle observations, which leads to an upper limit of 50 km for the diameter of any satellite with an albedo the same as or higher than Herculina.

Icarus 61, 232 (1985)

SPECKLE INTERFEROMETRY OF ASTEROIDS III. 511 DAVIDA
J. D. Drummond and E. K. Hege

511 Davida was observed with the technique of speckle interferometry at Steward Observatory's 2.3m telescope on May 3, 1982. Its dimensions were found to be (465 ± 33) x (358 ± 39) x (258 ± 52) km. Such a shape falls close to an equilibrium figure of a "rubble pile," suggesting a density of 1.4 ± 0.4 gm/cm^3. Simultaneous with the determination of the size and shape of Davida, we find its north pole to lie within 26° of RA = 19^h08^m, Dec = 15° (= 291°, = +37°).

These results for the pole and shape of Davida are consistent with the brightness/amplitude/aspect history of the asteroid, but the agreement can be improved if either an adjustment to the shape is made or an albedo gradient is postulated. For a Gehrels and Tedesco phase function, an adjusted speckle/photometry model of 425 x 345 x 324 leads to a visual albedo of .034 ± .002, but is not an equilibrium shape and does not allow a rubble pile. For our 465x358x258 figure, the albedo variation would have to be .031 to .040 from equator to pole. With the Lumme and Bowell phase function, an adjusted speckle/photometry model of 438x350x305 (also non-equilibrium) leads to a visual albedo of .042 C= .001, or a gradient of 0.037 to .044 from equator to pole for our 465x358x258 figure.

The precision of our present autocorrelation/power spectrum result, based upon only five ten minute observations, does not force a choice between a uniform albedo or an albedo gradient. Image reconstruction techniques presently under development may, however, permit such discriminations.

Icarus (Submitted - 1985)

PALLAS: AN ENIGMA

K. Hege and J. Drummond

Several controversial suggestions of an (unresolvable) satellite companion to Pallas have been neither confirmed nor refuted by speckle interferometry. Despite considerable success in arriving at a consistant interpretation of sets of speckle interferometric observations of other asteroids (notably Eros and Herculina), we have not been able to reconcile ambiguities in our observations of Pallas. Our most recent reductions suggest that, if Pallas has a satellite, it cannot be larger than 55km. The same ambiguities also suggest the need for true image reconstruction for their resolution.

(Unpublished)

SPECKLE INTERFEROMETRY OF ASTEROIDS IV. 12 VICTORIA

J. Drummond and K. Hege

A set of 2.3m telescope observations of 12 Victoria has been reduced to seeing calibrated autocorrelations. Tri-axial ellipsoid model interpretations await installation of current Point-Four microcomputer algorithms, presently encoded in FORTH, on the new Steward Observatory DG MV10000 superminicomputer in FORTRAN 77.

(Unpublished)

1.4 Image Reconstruction Experiments

The development of fundamental capabilities for speckle image reconstruction and of a basic understanding of the atmospheric processes involved in those imaging procedures has been the central objective of all of the Air Force sponsored optical image reconstruction efforts at Steward Observatory since the beginning of this program (initially sponsored by AFGL) in 1977 (See reports: AFGL-TR-78-1067, SD-TR-82-45, SD-TR-82-46, AFGL-TR-82-0136, and AFGL-TR-84-0116). Only recently has that belabored effort come to fruition. The following abstracts summarize the principle advances in image reconstruction technology during the last grant interval, beginning with two proposals for potentially realizable, real-time hardware systems for integration of image amplitudes and phases, one for Fourier transform (u,v)-plane integrations and the other for equivalent image (x-y)-plane integrations (for faint objects).

We have shown that several of the methods currently under investigation and in development yield valid point spread functions (aperture diffraction patterns) for point sources. This is the first crucial step in validation of these methods. The continuing work focuses on further validation and optimization of procedures for faint object image reconstruction.

HIGH-SPEED DIGITAL SIGNAL PROCESSING FOR SPECKLE INTERFEROMETRY
E. K. Hege, W. J. Cocke, P. A. Strittmatter, S. P. Worden and W. C. Booth

Speckle interferometry has now been shown capable of yielding diffraction limited information on objects as faint as visual magnitude 16. Research in progress at Steward Observatory is aimed at improving (a) the resolution, (by using the Multiple Mirror Telescope with its 6.86 meter baseline), (b) the accuracy, of the derived results (by implementing better recording devices and reduction algorithms), and (c) the efficiency and speed with which the information can be provided (by means of high-speed digital signal-processing hardware).

The instrument proposed here will improve spatial resolution at visible wavelengths to approximately 15 milliarc-seconds (75 x 10^{-9} radians, the best possible for any existing telescope), reduce the detector induced image distortion to less than 1% and increase the throughput to essentially real-time complex Fourier transform amplitude and phase integrations at the telescope.

Proc. SPIE 445, 469 (1983)

A REAL-TIME COMPLEX AUTOCORRELOGRAM INTEGRATOR

K. Hege and P. Vokac

Based on the recently developed algorithms for integrating image phases in the Knox-Thompson sense, photon-by-photon in the image, (x,y)-plane, we have outlined the design of a real-time image amplitude and image phase integration system. It is a logical extension of the amplitudes only image autocorrelogram integration presently used in a successful and productive observational program by McAlister. The complex (Re($_x$), Im($_x$)) and (Re($_y$), Im($_y$)) integrations will proceed exactly parallel to the existing amplitude integration, therefore causing no additional timing delays. Other refinements to the existing McAlister system include photon centroiding to a single pixel and frame-subtraction to suppress image intensifier lag. Estimated total cost (exclusive of host VME-bus, MC68000 system): $90K.

(Unpublished)

KNOX-THOMPSON PHASE RECOVERY PHOTON-BY-PHOTON

A. Eckart, J. Cocke and K. Hege

To obtain reliable maps from speckle interferometry data using amplitude and phase information, Nisenson, et al. 1980 proposed to use a set of four arrays, two of which contain the phase information. The phases used to Fourier transform the amplitude data (obtained from the autocorrelation) are given implicity as phase differences between adjacent grid points in the x and y directions. We have implemented a discrete photon version of this algorithm in which cosine and sine modulated sums over the photon coordinate llists are accumulated.

(Preprint)

USE OF "CLEAN" IN SPECKLE IMAGE CALIBRATION

A. Eckart, K. Hege, J. Christou and S. Shaklan

In order to deconvolve images of program sources with images of point like calibrator sources, attempts were made to use the "clean" procedure implemented in the Advanced Image Processing System (AIPS). This algorithm is applied to radio interferometric data in order to remove structural features due to the synthesized interferometer beam. We have recently applied it to remove

residual PSF effects in speckle interferometry, using images of an unresolved source, observed and reduced commensurately, to remove systematic artifacts from images of resolved sources.

(Preprint)

SEEING CALIBRATION OF OPTICAL ASTRONOMICAL SPECKLE INTERFEROMETRIC DATA
J. Christou, A.Y.S. Cheng and E.K. Hege

In this paper we show the effect of different seeing conditions, as parameterized by the atmospheric coherence scale r_o, upon standard Labeyrie analysis for independent observations of both a resolved object and its point source calibrator. Atmospheric dependent effects are shown by using both models and data. We show how to sort the data into like seeing bins in order to produce a calibrated image power spectrum estimate. We also justify using a stronger weighting of intermediate spatial frequencies in the image power spectrum estimator when fitting physical paramaters constrained by image power spectrum estimates.

Astron. J. (Submitted - 1985)

SEEING STUDIES FOR SPECKLE HOLOGRAPHIC IMAGING
J. Christou and K. Hege

The two-fold purpose of this study is to quantitatively evaluate the degree of isoplanicity in a particular speckle holographic measurement and to propose a technique for reweighting speckle holographic cross-spectrum amplitudes in order to recover quantitatively correct, diffracton limited speckle holographic images.

(Preprint)

SPECKLE IMAGE RECONSTRUCTION: WEIGHTED SHIFT-AND-ADD ANALYSIS
J.C. Christou, E.K. Hege, J. Freeman, P.A. Strittmatter

A number of image reconstruction methods have been applied to speckle interferometric data obtained at Steward Observatory. This paper will concentrate on the Weighted Shift-and-Add (WSA) analysis which is an extension of the method proposed by Lynds, Worden & Harvey (LWH). This method creates an impulse frame for each specklegram which consists of zeros everywhere except at the loci corresponding to the local maxima of the specklegram. At these loci the impulse frame takes on the values of the specklegram. Letting the specklegram be $d_i(x,y)$ and the weighted impulse frame be $s_i(x,y)$ then we compute

$$I_i(x,y) = [FT\{d_i(x,y)\}/FT\{s_i(x,y)\}]\ |FT\{s_i(x,y)\}|^2,$$

(where FT denotes the complex Fourier Transform) and sum I_i (x,y) over the ensemble $\{i\}$ of specklegrams. Dividing this sum by the

sum of the weighting moduli $|FT\{s_i(x,y)|^2$ and inverse transforming produces the WSA image. The advantage of this method over that of LWH and Bates' conventional shift-and-add analysis is that it eliminates the residual "seeing" produced background which remains in those methods. Application of this technique to a number of resolved and unresolved objects have been performed and results will presented and discussed.

B. Am. Astr. Soc. **16**, 185 (1984)

SELF-CALIBRATING SHIFT-AND-ADD TECHNIQUES
J. Christou, E. Ribak, K. Hege, and J. Freeman

We describe a new speckle image reconstruction technique which preserves phase information by using the full, complex Fourier transform rather than Fourier moduli, at each processing step. The method appears to be fully self-calibrating for seeing effects. Independent measures of unresolved point sources, also self-calibrated for seeing effects, can be used as "dirty beams" with the algorithm CLEAN, as used in radio astronomy to produce true diffraction limited images (maps) of extended sources with calibrated amplitudes and with seeing and aperture effects removed. Our new method is a derivative of the shift-and-add technique pioneered by Lynds, Worden and Harvey and by Bates. Use of matched filter techniques, for location of individual local speckle maxima, extends the procedure to applicability in the Poisson statistics limited case.

J. Opt. Soc. Am. A (Submitted - 1985)

MATCHED FILTERS AND SHIFT-AND-ADD SPECKLE IMAGE RECONSTRUCTION
E. Ribak, K. Hege, J. Christou, and J. Freeman

We have investigated an interative technique to determine the mean speckle in a set of Poisson noisy astronomical specklegrams. When the method is coupled with a recently developed weighted deconvolved shift-and-add procedure, the result is self-calibrated for seeing effects for sufficiently bright objects, but may only be applicable to the seeing biased Bates shift-and-add method in the extreme Poisson noise limits. We have demonstrated results for point sources and binary stars, and propose investigating the applicability of the method to broad sources without a well-defined local maximum.

(Unpublished)

IDENTIFICATION OF SPECKLES BY MATCHED FILTERING
E. Ribak, E. K. Hege, and J. C. Christou

The shift-and-add analysis was devised to retrieve amplitude and phase information from speckle data. Various realizations of this analysis require identification of reference points in either the brightest speckle or all speckles in each frame. This is not

always possible when the speckle maxima are ill-defined (such as when the noise level is too high, or the object is a binaary). Locating speckle centroids by use of matched filtering can help to solve this problem. A filter is correlated with the frame, producting a two-dimensional function whose maxima represent speckle loci and power. The standard shift-and-add methods are then used to reconstruct the image according to these maxima. The approach is iterative, since the matched filter is a function of the accumulated speckles, and is up-dated constantly. A gaussian bell, wider than the estimated object size, can serve as an initial guess. The filtering and the speckle addition can be done in either the image or the Fourier plane.

B. Am. Astr. Soc. **16**, 885 (1984)

2. SCIENTIFIC ACCOMPLISHMENTS

The work just completed contained a major emphasis on astronomical science. Our showpiece scientific accomplishments are the set of asteriod/planetary satellite results reviewed above in Section 1.3 in the context of their relevance to current space object identification requirements, and the set of images of the red supergiant Betelgeuse.

2.1 Asteroid/Planetary Science

Our work on speckle interferometric observations of asteroids is unique thus far in that we are the only group routinely making direct measurements of the three axis dimensions and the spin axis directions of small (0.5- 0.05), faint (10-12 mag), moving objects observed over only one or two nights. We have obtained the dimensions and pole of the Earth-approaching asteroid 433 Eros, confirming the results obtained by other indirect, long-term, methods. Similarly, we have measured the size, shape, and pole of 532 Herculina and found no evidence of a satellite (as suggested by a secondary event during an observed occultation of a star), but found, instead, a large bright spot on the surface of the asteroid.

The dark asteroid 511 Davida was found to be rather oblate in shape, suggesting that it could be in hydrostatic equilibrium, a thoroughly fractured rubble pile. Moreover, we found evidence that it may have a brightness gradient from pole to equator. In addition to its dimensions and pole, we found its bulk density to be 1.5 gm/cm^3 if it is indeed an equilibrium figure.

Our continuing work on the Pluto/Charon system resulted in a telegram with the prediction that when Pluto next became favorably placed in late December 1984 or January 1985, the long awaited, once in a lifetime series of mutual eclipses would begin. This was confirmed 16 January 1985.

Continuing work includes interpreting our observations of 2 Pallas which appears to be so spotted that unambiguous results have not been possible. We are on the verge of obtaining images (see collaborative effort, section 3.2) as well as the dimensions and pole of the brighter asteroid 4 Vesta. We have in hand observations of some 8-10 other asteroids awaiting reduction. Based on our experience with those already reduced, which have turned out to be far more interesting than simple, smooth, uniform, triaxial ellipsoids, we desire to push our efforts to obtain not just autocorrelations or power spectra from which to make our measurements, but to obtain reconstructed images.

2.2 Red Supergiants: Limb Darkening/Extended Atmospheres

We are presently achieving our best success in speckle image reconstruction in our program of observations of bright, red supergiants. Weighted shift-and-add with deconvolution is our method of choice for this work which, for point sources, clearly yields results with the seeing bias removed. Figures 2 and 3 show the results displayed as azimuthal averages for several bandpasses using the KPNO 4 meter telescope. The theoretical

diffraction limited profiles are superimposed for comparison. Figure 3 also contains a similar display for the red supergiant Betelgeuse with the measured point xource response superimposed for comparison.

Figure 4 shows an example of a full two-dimensional reduction, this time observed with the Steward 2.3 meter telescope. The point source response (contaminated by detector systematics) was used to clean the resolved object measurement (both at 656.3nm) yielding a result showing a round central response due to the stellar photosphere and an elongated, extended stellar atmosphere.

The set of 4m telescope measures of Betelgeuse has been analyzed, using models in image space, fit in a least squares sense to seeing calibrated speckle image power spectrum profiles. This yielded the first ever set of estimates of stellar limb darkening. The results were observationally compromised by the marginal resolution of the 4m telescope (see Figure 3), showing the need for measurements using the larger, cophased MMT aperture.

The first diffraction limited image results with the MMT have been achieved using differential speckle interferometry (DSI). Figures 5 and 6 show our first reduction for Betelgeuse at the full resolution of the MMT. Each of these differential images represents about 1000 differential specklegrams for each of two sky position angles. The narrow band H results show an extended stellar atmosphere as well as evidence for structure, just resolved at the diffraction limit of the MMT, within the diameter of the photosphere. This small scale resolved feature has position angles differing by just the amount of the sky rotation between these two views, yielding strong confirmation that the feature is truly a stellar feature and not an instrument artifact (the position angle of the instrument did not rotate between these two views). The MMT DSI point

spread function obtained from the unresolvable star Gamma Orionis is shown in Figure 7 for comparison.

THE PHYSICAL DIAMETER OF ALPHA ORIONIS?
A. Y. S. Cheng, P. A. Strittmatter, E. K. Hege, B. N. Hubbard
L. Goldberg and W. J. Cocke

Previously reported speckle interferometric measurements of the angular diameter of Alpha Orionis are widely scattered and apparently inconsistent, ranging from 70 ± to 30 ± mas. Stellar atmosphere models predict a stellar disk to be limb-darkened differently for different spectral features. Upon analysis of well-calibrated speckle observations of Alpha Orionis obtained at various wavelengths with the KPNO 4 meter telescope, we are able to account for both the scattering of the previous speckle measurements, as well as our new results, in terms of a fixed physical stellar diameter with spectral feature dependent limb-darkening coefficients. We find the angular diameter of Alpha Orionis is 50 mas with limb-darkening (cosine model) coefficients ranging from about 1 in TiO absorption bands to about 0.4 in CaII absorption lines.

Astrophys. J. (In preparation - 1985)

IMAGES OF ALPHA ORIONIS?
J. C. Hebden, J. C. Christou, A. Y. S. Cheng, E. K. Hege,
P. A. Strittmatter and J. M. Beckers

Between February 1981 and December 1983 a series of speckle interferometric observations were made of the M-type supergiant Alpha Orionis in an attempt to produce two-dimensional images of the star at the hydrogen-alpha line. The telescopes employed include the Steward Observatory 2.3 meter and NOAO 4 meter at Kitt Peak and the fully-phased six-mirror Multiple Mirror Telescope at Mount Hopkins. Various data reduction techniques were applied which divide into two main catagories: i) Shift-and-Add methods applied to conventional speckle interferometric observations, and ii) Differential speckle interferometry. Data reduction also included the application of the CLEAN algorithm to calibrate the images produced by the Shift-and-Add technique with data reduced similarly for a point source. The images produced are encouragingly consistent in suggesting the atmospheric structure they exhibit and a possible observed evolution of the structure over the three year period of observations is proposed.

Astrophys. J. (In preparation - 1985)

2.3 Binary Stars

No new binary star measurements were made during this study since it is essential that calibration and validation work be completed before any further scientifically relevant observations be attempted. Although McAlister has a long established program of successful (ρ, θ) measurements of binaries, for the work we originally proposed the more difficult relative magnitude retrieval (individual component photometry) is also essential.

Measurement of the relative intensities of the components is not only a fundamental problem in measurement of close binaries, but also this, together with measurement of the orientation (phase) constitutes the simplest image reconstruction (a two resolution element image). It is, therefore, of fundamental relevance to assure that speckle methods yield well-calibrated results in this application, as this constitutes the second step in validation of image reconstruction methodology—having shown first (see section 1.4) that the point source response (PSF) is valid.

Our principle binary star work is the comparative study of various methods, also in collaboration with other groups (see sections 3.1 and 3.3), to measure systems for which the relative component intensity is known, especially the well-known binary Capella. We have also found simple experiments with a simulated data set to be useful.

RECOVERY OF SPECKLE IMAGE AMPLITUDES FOR BINARY STARS:
A COMPARISON OF TECHNIQUES

K. Hege, W. Bagnuolo, J. Christou, J. Freeman, J. Cocke and D. Granrath

We have subjected a set of simple, photon-noise free simulated specklegrams for a triple star, for Capella and for the Lunar occultation binary 115 TAU to various image reconstruction processses in order first to check their ability to retain quantitative relative amplitude information and second to compare the computational efficiency of the algorithms. An amplitude squared weighted shift-and-add cross-correlation gives the most direct estimation of the relative amplitudes and orientation. A

weighted shift-and-add deconvolution gives that, as well as a seeing self-calibration, when matched filter techniques are used to located individual speckles. A screened shift-and-add method is also quantitiative, but like the amplitude squared cross-correlation includes a seeing bias. Both are computationally straight forward, and the seeing bias can be effectively modelled with a Gaussian profile and subtracted away. The Knox-Thompson technique, and a phase unwrapping scheme also are quantitative, and when combined with low-frequency amplitude calibrations given by contemporaneous observations of a point source calibrator, give good amplitude fidelity and seeing compensation. These last two methods are the most computationally expensive, but the best understood theoretically. All of the methods appear to give equivalent fidelity to the original source when applied to the same data. A maximum norm power spectrum method was also applied to the Capella data set and found to produce good relative amplitude recovery, but (because it is a power spectrum technique) it does not give quadrant resolution.

Astron. J. (In preparation - 1985)

2.4 Active Galactic Nuclei

The fundamental question about an active galactic nucleus is What is the nature of the non-stellar energy component? This includes such a fundamental question as How big is it? Conventional methods of surface photometry and high-resolution spectroscopy can establish only rough upper bounds and are subject to ambiguities due to star light contamination. We have used speckle interferometry to improve the upper bounds to the spatial extent of the nuclear continuum source and to improve the resolution of the nuclear stellar bulge. Preliminary measures of the nucleus of NGC 1068, a type 2 Seyfert galaxy, show a nuclear stellar bulge of about 0."6 FWHM and an unresolvable continuum component in recent measures with the 2.3m telescope. New data was obtained with the KPNO 4m telescope to improve these estimates. A source unresolved at 0."050, the resolution of the 2.3m telescope, cannot be larger than about 4 pc at its presumed distance of 15 Mpc. Present evidence suggest further that it is probably not larger than 0."016, but confirmation awaits reduction of the new 4m data set.

SPECKLE OBSERVATIONS OF THE NUCLEUS OF NGC 1068
M. Malkan, K. Hege, P. Strittmatter

We have used the University of Arizona 2.3m telescope to obtain specklegrams of the nucleus of NGC 1068. Observations were made with violet, green, and far-red continuum filters, selected to exclude contamination from strong emission lines. Most (75-80%) of the green (~550nm) nuclear light (in the central 3 arc seconds) is concentrated in an unresolved point source. A comparison with the profiles of field stars indicates that this point source is no larger than 16 milliarc seconds, corresponding to a radius of less than half a parsec. By comparing the relative contributions of the point source at each wavelength, we determine its colors. Implications for the nature of this nonstellar point source will be discussed. The extended (starlight) component of red light is analyzed in conjunction with conventional surface photometry of Malkan and Oke (1983) to search for a stellar cusp within the central arc second of the galactic bulge.

B. Am. Astr. Soc. 16, 987 (1984)

2.5 QSO Images

Most objects of cosmological interest are at the extreme faint limit of applicability of speckle interferometry techniques. It is possible to partially correct images for long-term, low-frequency effects, to produce a result limited only by the "instantaneous" (1/60 sec for video exposures) seeing. We have developed a post processing technique, which we call rapid guiding, to superimpose a set of focal plane images so that the centroid of energy of each is coadded at the same location in the final result. This was used to produce an image of exceptional quality in spite of large air mass (65° zenith angle) of the 16th magnitude QSO PG 1115 +080. This object is seen as a multiple component image produced by the gravitational lens effect of an intervening galaxy. Our imagry has been analyzed to show the first direct detection of that galaxy, confirming gravitational lens predictions of general relativitiy.

THE GRAVITATIONAL LENS IN PG 1115 +080
S. B. Shaklan and E. K. Hege

We have fit models to high resolution (0.6 arc sec) post-guided observations of the triple quasar in blue and red light. The four components (A, A', B, and C) all have similar point spread functions in the blue fit. There are no significant blue residuals after subtraction of the model for the image. The fits to components A, A', and C in the red image are consistent, but the B component of the red image suggests that there is an excess red flux from an area between all four components. The red residuals show that this flux has a magnitude of 19.8 ±0.3 in the R band, and a V-R color of at least 2.7 ±0.5. The flux's position is consistent with that of the lensing galaxy in models of gravitational imaging.

Astrophys. J. (In preparation)

3. COLLABORATIVE EFFORTS

One of the many productive recommendations growing out of the AFOSR sponsored Oracle Conference on Speckle Imaging (An AFOSR sponsored 1982 showpiece achievement) was that collaborative efforts to apply and analyze the results of various methods of speckle image reconstruction applied to the same data sets would be very valuable. Since then we have shared data and otherwise collaborated with groups at Aerospace, Harvard, in New Zealand and with several local Tucson groups.

IMAGE RECONSTRUCTION FROM ASTRONOMICAL SEPCKLE INTERFEROMETRY
E. Hege, C. Dainty and C. Papaliolios

The goal of achieving diffraction limited images from specklegrams obtained at ground-based telescopes now appears to be within reach. A number of groups in several countries have contributed to this advance. We therefore organized an informal workshop on the subject with participation limited to those actively involved in the field. Fifty participants presented an overview of their work and discussed problems and progress.

(Steward Observatory Report)

3.1 The Aerospace Corporation

In collaboration with Drs. William Bagnuolo, Jr. and Eric Jensen of Aerospace, we have, i) investigated the performance of the shift-and-add

algorithm in recovery of binary star component intensity information (Simulated data, Capella and 115 Tau—see section 2.3), in recovering faint extensions to bright resolved objects (Betelgense) and in recovering images of extended objects with more than one local maximum (Simulation of, e.g. a typical active galactic nuclear region). ii) made observations of synchronous (FLTSATCOM1) and semi-synchronous (Molniya) satellites using the MMT (cf. section 1.2). We have also assisted in Aerospace implementation and testing of Knox-Thompson and phase unwrapping (Cocke) image reconstruction software.

We have also supplied (and continue to supply) astronomical data to Bagnuolo and Jensen for use in evaluation of various shift and add image reconstruction approaches.

IMAGE RESTORATION VIA THE SHIFT-AND-ADD ALGORITHM
William G. Bagnuolo, Jr.

A new method for image restoration based on the shift-and-add algorithm is presented, the main advantages of which appear to be speed and simplicity. The shift-and-add pattern produced by an object is given by the object correlated by a non-linear replica of itself whose intensity distribution is strongly weighted toward the brighter pixels. A method of successive substitutions analogous to Fienup's algorithm can then be used to "decorrelate" the SAA pattern and recover the object. The method is applied to the case of the extended chromosphere of Betelgeuse.

Optics Letters 10, 200 (1985)

3.2 The Harvard Group

The principal component of the Harvard collaboration, with Drs. P. Nisenson and C. Papaliolios has been observations made with the 2.3m telescope and with the MMT to evaluate the effectiveness of the prototype model of the PAPA detector.

This collaboration produced the Pluto measurement noted in section 1.3 and observations leading to a set of time-resolved image reconstructions of

Vesta. These successes have led to our implementation of the photon-by-photon Knox-Thompson phase retreval capability noted in section 1.4.

SPECKLE IMAGING WITH THE PAPA DETECTOR
C. Papaliolios. P. Nisenson and S. Ebstein

A new two dimensional photon-counting camera, the PAPA (Precision Analog Photon Address) detector has been built, tested and used successfully for the acquisition of speckle imaging data. The camera has 512x512 pixels and operates at count rates of at least 200,000 per second. In this paper, we present technical details on the camera, and include some of the laboratory and astronomical results which demonstrate the detector's capabilities.

Applied Optics 24, 287 (1985)

KNOX-THOMPSON IMAGING OF 4 VESTA
K. Hege, J. Drummond, C. Papaliolios, P. Nisenson, and S. Ebstein

In a collaborative investigation, the PAPA detector, a two-dimensional, photon-counting imaging system was used to obtain a set of observations of Vesta. These were reduced at Harvard/SAO to yield seeing calibrated image autocorrelation fucntions and Knox-Thomson reconstructed images. This data set is to be analyzed at Steward Observatory using techniques developed (for asteriod 433 Eros) by Drummond and Cocke.

(Unpublished)

3.3 The New Zealand Group

In discussion, and collaborations in which we have supplied astronomical data to validate procedures otherwise only tested in simulations, we have associated with Dr. R.H.T. Bates and his New Zealand coworkers in studies of partially isoplanatic speckle holographic imaging (α_1, α_2 SCO), phaseless speckle image reconstruction (433 Eros) and in a question of whether (or what fraction of the energy of) speckles scale with wavelength.

"PHASELESS" IMAGE RECONSTRUCTION: 433 EROS
R. H. T. Bates, E. K. Hege and J. D. Drummond

An image of asteroid 433 Eros has been obtained from its calibrated amplitudes only using the method proposed initially by Fright and Bates. The result is comparable to that produced by the Fienup method. When combined with the Fienup method, the result converges with less computation than the Fienup method alone. Eros is shown to be an elongated, non-uniformly illuminated object.

Astron. J. (In preparation)

SHIFT-AND-ADD IMAGING THROUGH PARTIALLY ISOPLANATIC SEEING
R. H. T. Bates, A. M. Sinton, E. K. Hege, J. C. Christou and J. M. Beckers

The effect of partial isoplanatism on shift-and-add images is shown to reduce their contrast but not their intrinsic faithfulness. Conversely, the faithfulness of Labeyrie's speckle interferometry, and of its extension due to Knox and Thompson, is found to be adversely affected by partial isoplanatism. A suggestion is made for employing shift-and-add to search the darker regions of the celestial sphere for faint detail. The discussion is illustrated with computational examples.

Mon. Not. R. Astr. Soc. (In preparation - 1985)

DO SPECKLES SCALE WITH WAVELENGTH?
R. H. T. Bates, J. M Beckers, J. C. Christou, E. K. Hege and A. Szumilo

If some significant fraction of the speckle energy scales with wavelength, then simultaneously observed specklegrams at two quite different wavelengths can be used in an iterative image reconstruction algorithm to produce an image at the resolution of the telescope in the longer of the two wavelengths.

(Unpublished)

3.4 Other Local Collaborations

We have also worked in mutual studies with other non-Steward Observatory investigators in Tucson. The most important of these are i) the continuation of the differental speckle interferomety project with Dr. J. M. Beckers now at National Optical Astronomical Observatories, (NOAO), ii) with Drs. Claude and Francois Roddier, also at NOAO in seeing studies and statistical analyses relevant to the processes of speckle

interferometry, and iii) with D. Granrath of Science Applications International Corporation to whom we supplied sets of data for the purpose of evaluation of a maximum norm method for recovering an image power spectrum minimally distorted by atmospheric perturbations.

THE DIFFERENTIAL SPECKLE INTERFEROMETER
J. M. Beckers, E. K. Hege and H. P. Murphy

We describe a new technique called "Differential Speckle Interferometry" (DSI) which uses simultaneous narrow band images of astronomical objects to study their structure. Simultaneous specklegrams of red supergiant and giant stars taken in the hydrogen lines and in the nearby continuum allow us to reconstruct the image of the extended chromospheres of these stars at resolutions of 100 nanoradians and better. We describe the instrumentation, analysis techniques, and results related to DSI.

Proc. SPIE 445, 462 (1903)

CALIBRATION OF AN INSTANTANEOUS SPECKLE SEEING ESTIMATOR
J. Christou, C. Roddier, F. Roddier and K. Hege

We are using contemporaneous measurements of seeing at the Steward Observatory 2.3m telescope with a pupil shearing interferometer and a convential image plane speckle camera in order to calibrate a recently proposed focal plane specklegram measure of instantaneous (i.e. short exposure) seeing.

(Unpublished)

STATISTICAL ANALYSIS OF THE SELF-CALIBRATING
SHIFT-AND-ADD IMAGE RECONSTRUCTION TECHNIQUE
J. Freeman, K. Hege, J. Christou, E. Ribak and F. Roddier

We demonstrate the underlying statistical basis for the Christou, Ribak and Hege technique for recovering a mean speckle image. Our analysis of this method, which is a logical extension of the simple shift and add technique pioneered by Bates and Lynds, Worden and Harvey, is a logical extension of an earlier study by Hunt, Fright, and Bates of the Bates technique.

(Preprint)

MAXIMUM MAGNITUDE ESTIMATION OF THE OBJECT'S POWER SPECTRUM IN STELLAR SPECKLE INTERFEROMETRY
D. J. Granrath

The maximum Fourier magnitude taken over a set of speckle images is proposed as a replacement for the standard power spectrum average. This new statistic estimates the diffraction-limited object-times-telescope magnitude values in a statistically unbiased and sufficient fashion, and has a variance that decreases with sample size faster than the average magnitude's variance. Simultaneous imaging of a nearby point source is unnecessary with this technique, and any object that lies within a single isoplanatic patch of the atmosphere can be estimated. Magnitude estimation results of the double star Capella are shown to corroborate these claims.

Optics Letters, 9, 478 (1984)

4. THE LARGE OPTICS PROJECT

A closely related activity at Steward Observatory is the development of large lightweight optical reflectors and the study of their potential use in ultra-high resolution optical imaging array configurations.

THE VERSATILE ARRAY
N. J. Woolf, J. R. P. Angel, and D. W. McCarthy

We discuss a four element non-degenerate array telescope-interferometer for ground use. The elements are 8 meter mirrors, and the maximum array spacing and two element spacing are 75m and 108m respectively. The array may be used as three separate telescopes, one 11.3m and two 8m for work not requiring highest angular resolution. We discuss the problems of making speckle measures to high enough precision for synthetic images to be produced. We conclude by showing that the high resolution presents opportunities to make types of observations that are neither possible with VLBA nor NNTT.

Proc. SPIE **444**, 78 (1983)

ALIGNMENT AND PHASING DEPLOYABLE TELESCOPES
N. Woolf and B. L. Ulich

We describe the experience in coaligning and phasing the MMT, together with studies in setting up radio telescopes. We discuss these experiences and on the basis of them we suggest schemes for coaligning and phasing four large future telescopes with complex primary mirror systems. These telescopes are MT2, a 15m equivalent MMT, The University of California Ten Meter Telescope, the 10m sub-mm wave telescope of the University of Arizona and the

Max Planck Institute for Radioastronomy, and the Large Deployable Reflector, a future space telescope for far IR and sub-mm waves.

ESO Workshop "Site Selection for Very Large Telescopes" (1983)

ADAPTIVE OPTICS

N. J. Woolf

Adaptive optics is a technique for correcting atmospheric wavefront disturbances to yield diffraction limited imaging. It is a technique whose advantages are most apparent in the 2-5u spectral region, where wavefront corrections are derived from study of visible objects. Graphs are presented to show performance needs of adaptive optics systems.

Proc. IAU Colloq. **79**, 221 (1984)

VERY LARGE GROUND-BASED TELESCOPES FOR OPTICAL AND IR ASTRONOMY

J. R. P. Angel

Optical and IR astronomers are taking a hard look at their ground-based facilities and devising new ways of making more economic, bigger and better telescopes. Features of instruments of the 15-m class are likely to include servo control to compensate for atmospheric wavefront errors as well as structural deformation, large honeycomb mirror blanks and mirror sufaces produced by economical techniques developed for aspherics.

Nature **295**, 651 (1982)

5. FIGURES

Figure 1. Point spread function for phased Multiple Mirror Telescope. Accumulated from 1000 specklegrams of γ ORI observed in a 1.3Å bandpass near 6563Å using the weighted-shift-and-add with deconvolution algorithm.

Figure 2. Same as 1 for 4m Telescope. The upper panels compare computed Airy pattern (left) with actually measured pattern (right). The lower panel shows the corresponding azimuthally averaged radial profile.

Figure 3. (Upper) Point spread functions for KPNO 4 m telescopes compared to theoretically computed optical transfer functions for different optical pass bands.

(Lower) Resolved object response functions for α ORI compared to the corresponding γ ORI PSF's for different optical pass bands.

Figure 4. α ORI image in H_α light produced by weighted shift-and-add (upper left). γ ORI (upper right) was observed and reduced similarly. The final result for α ORI (lower) was produced by using γ ORI as "dirty beam" in CLEAN algorithm to yield image with beam (PSF) artifacts removed.

Figure 5. Differential (DSI) image of α ORI obtained at the diffraction limit of the MMT. In this technique, image differences (in a deconvolution sense) between observations in H_α light and a nearby wavelength are compared. Evidence for a bright, elongated H_α feature are seen. 1000 different specklegrams were processed.

Figure 6. Same as 5 obtained with the field of view rotated (consequent to apparent sky rotation induced by the MMT's altazimuth mount). That the feature persists even though the apparent sky position angle changed by 82^{o} is strong validation of this result.

Figure 7. DSI point spread function, obtained from 1000 differential specklegrams of γ ORI in the same way as done for α ORI shown in figures 5 and 6.

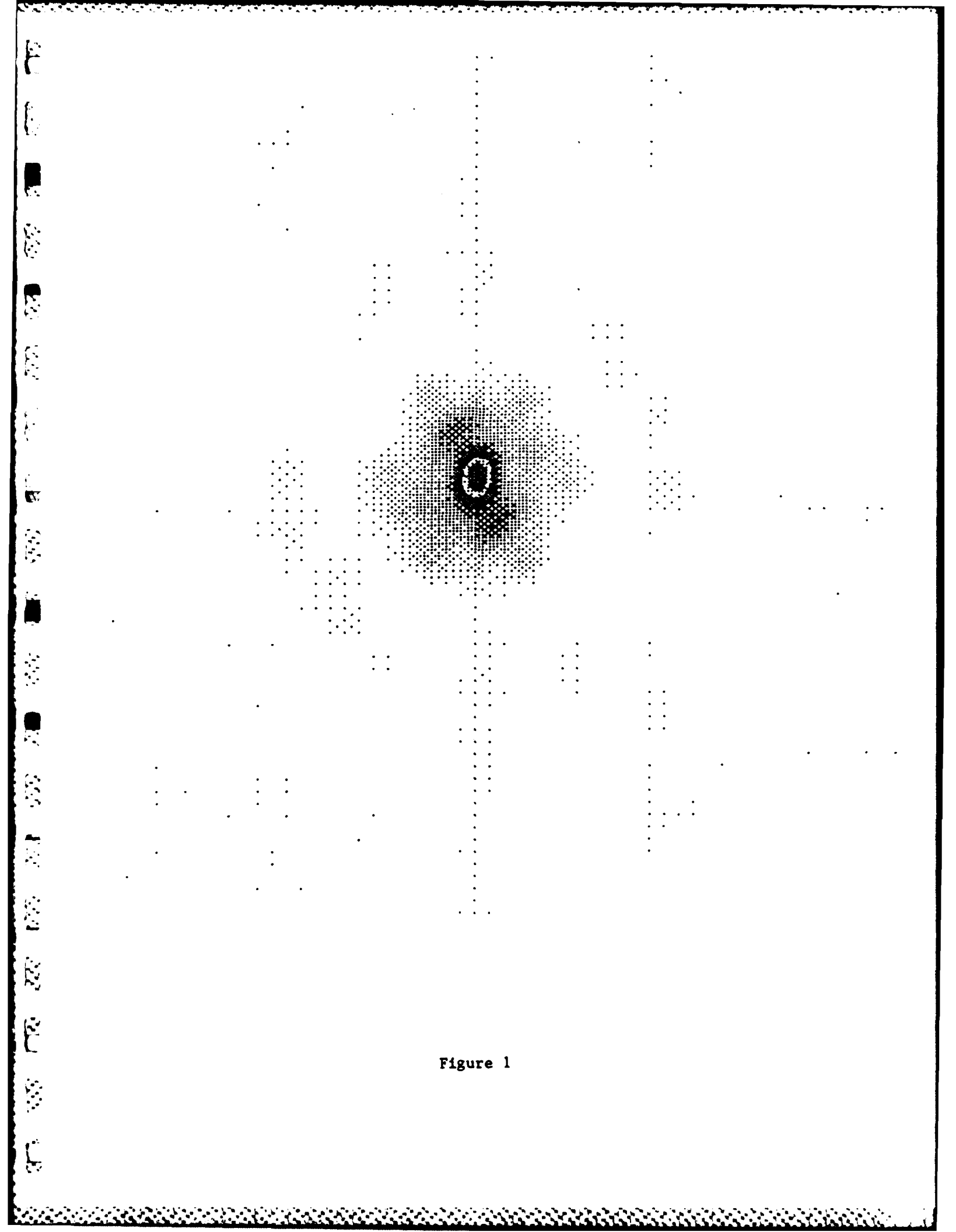
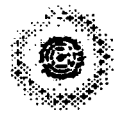
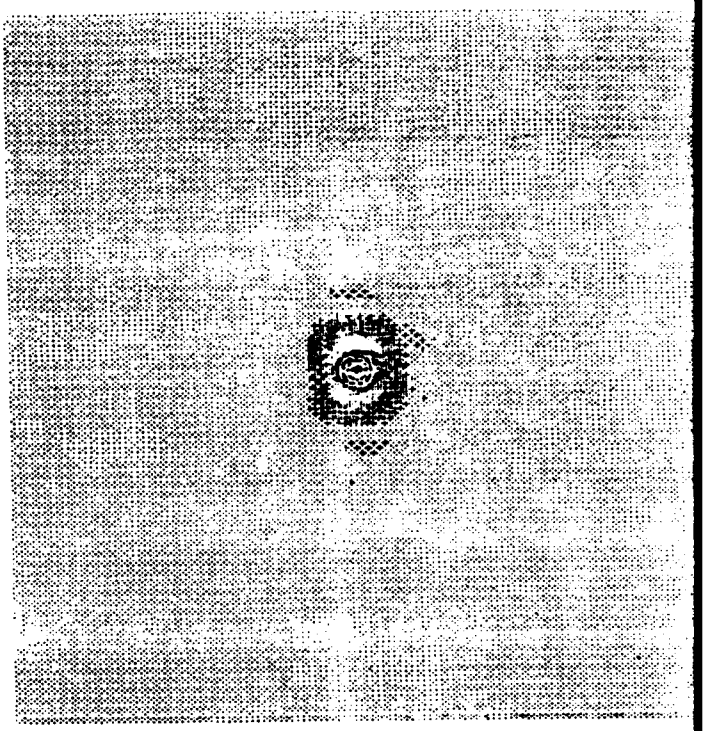


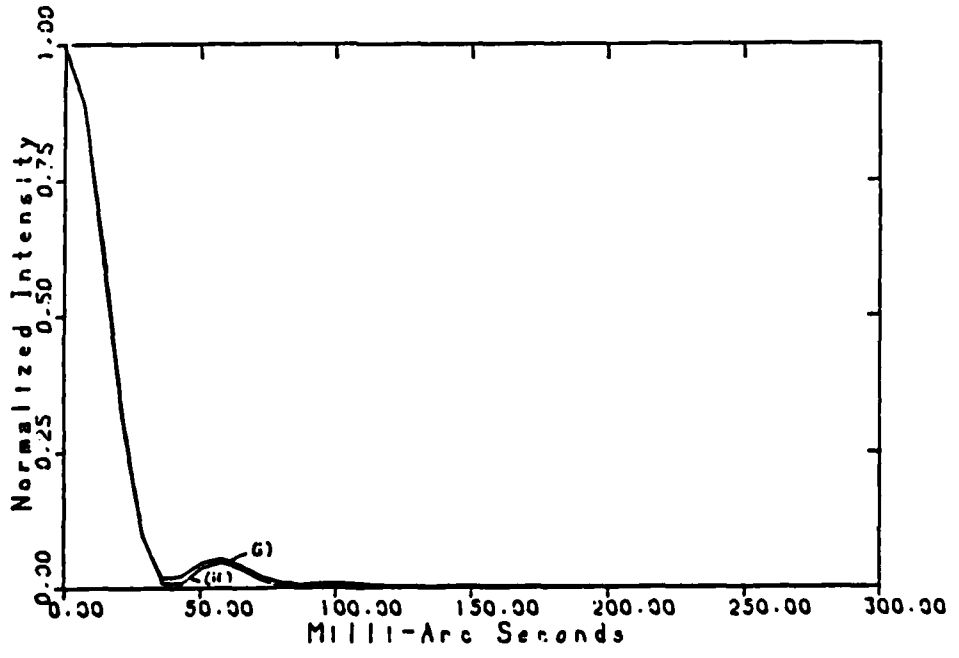
Figure 1



(a)

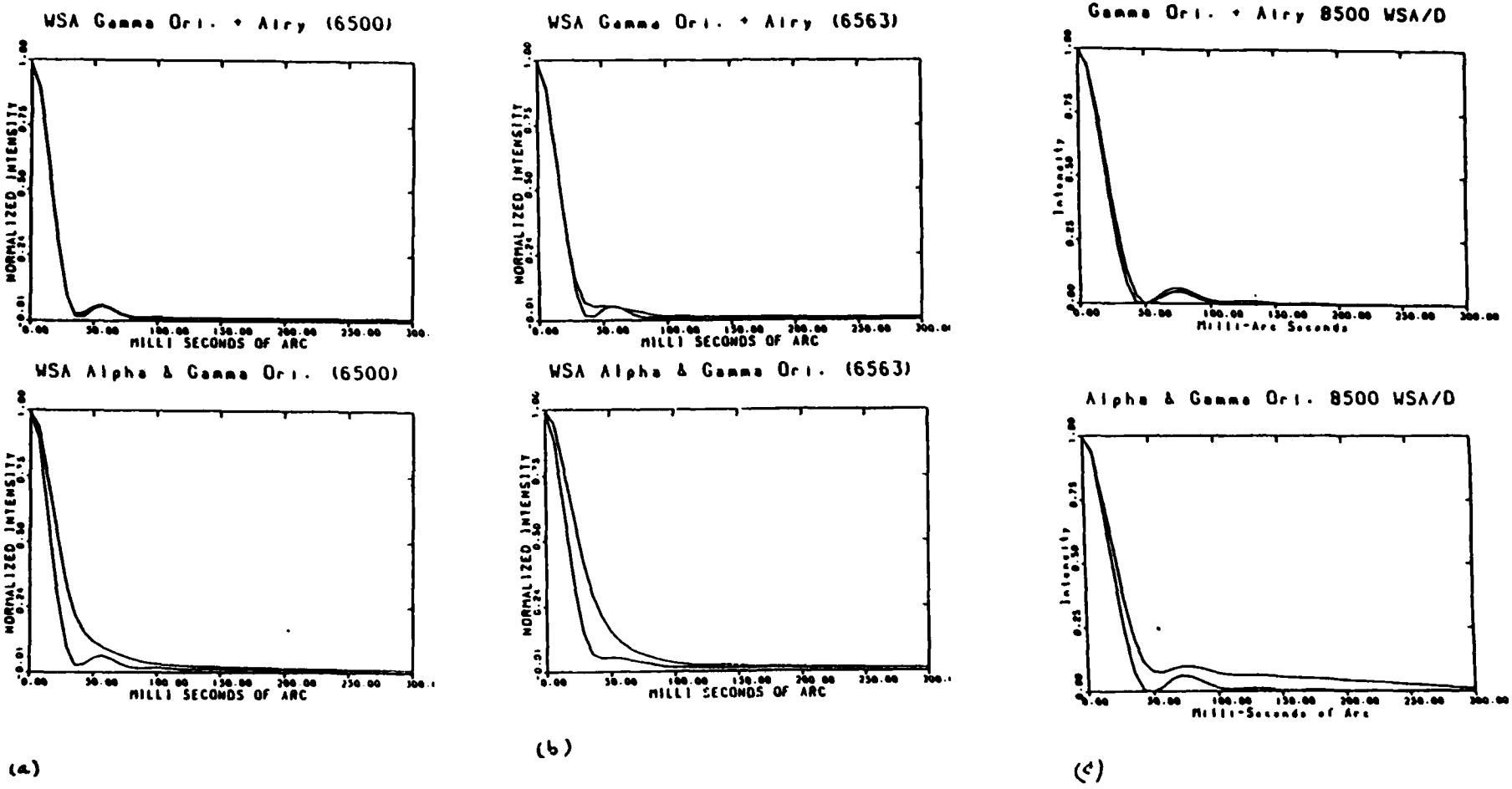


(b)


Normalized Intensity
1.00
0.75
0.50
0.25
0.00
0.00
50.00
100.00
150.00
200.00
250.00
300.00
Milli-Arc Seconds
(i)
(ii)

(c)

Figure 2


WSA Gamma Ori. + Airy (6500)
WSA Gamma Ori. + Airy (6563)
Gamma Ori. + Airy 8500 WSA/D
WSA Alpha & Gamma Ori. (6500)
WSA Alpha & Gamma Ori. (6563)
Alpha & Gamma Ori. 8500 WSA/D
NORMALIZED INTENSITY
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Intensity
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(a)
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(c)

Figure 3

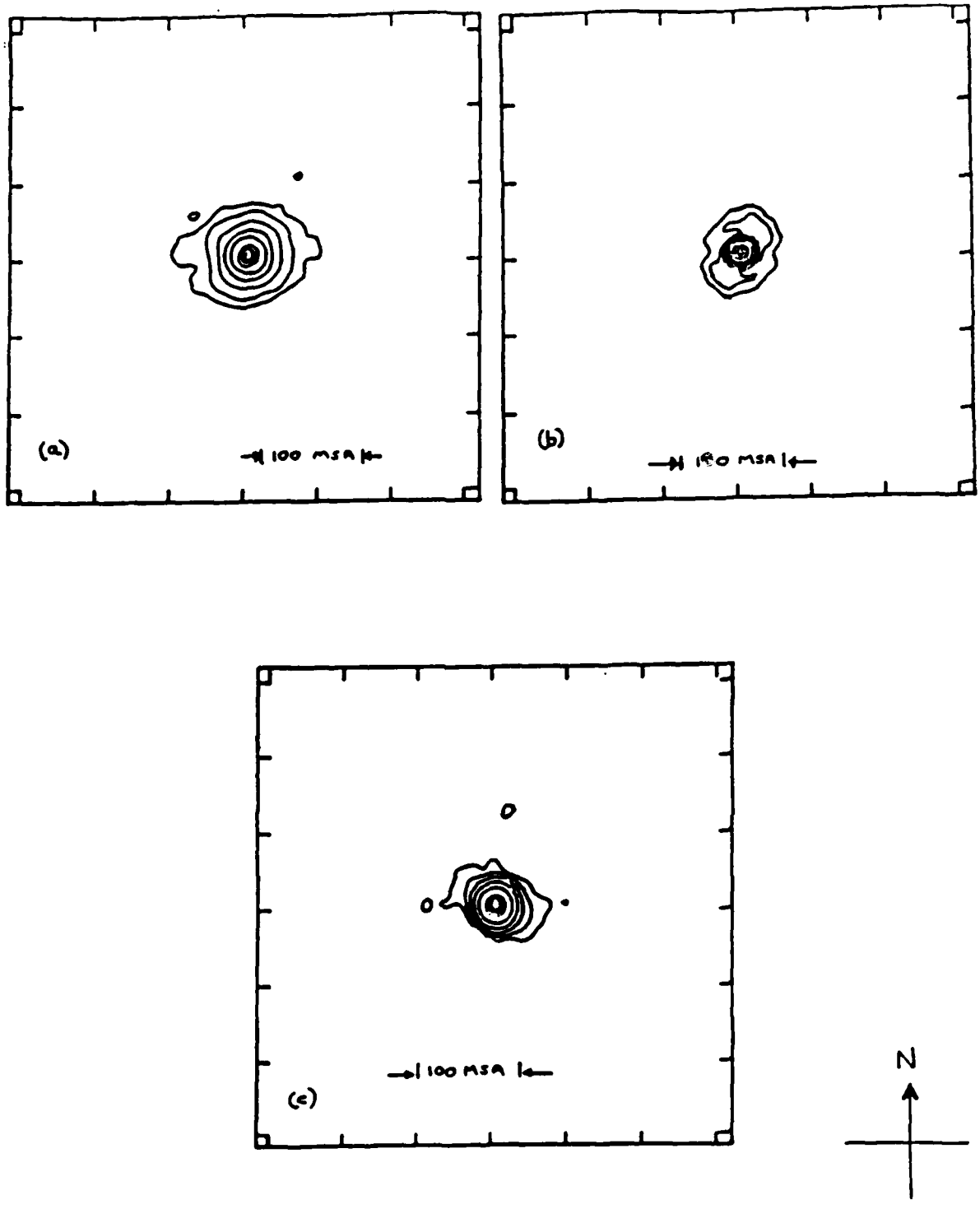

Figure 4

Figure 5

Figure 6

Figure 7

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